

Distributed processing of biomass to bio-oil for subsequent production of Fischer-Tropsch liquids

Mark M. Wright and Robert C. Brown, Iowa State University, USA
Akwas A. Boateng, US Department of Agriculture, Pennsylvania, USA

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Abstract: This study compares centralized processing to distributed processing of biomass for subsequent production of Fischer-Tropsch liquids (FTLs) at a centralized catalytic synthesis facility. Distributed processing in this study is based on fast pyrolysis to bio-oils, which are more economically transported to a centralized F-T plant where bio-oil is gasified and the syngas catalytically converted to FTLs. The study indicates that a centralized gasification plant can produce FTLs from biomass for \$1.56 per gallon of gasoline equivalent (gge) in an optimally sized plant of 550 million gge per year. Three distributed processing systems were investigated based on the scale of biomass processing capacity: 'on-farm' pyrolyzers of 5.4 ton per day (tpd) capacity; 'small cooperative' pyrolyzers of 55 tpd capacity, and 'large cooperative' pyrolyzers of 550 tpd capacity. Distributed processing is combined with very large centralized bio-oil processing plants that accept bio-oil for catalytic upgrading to transportation fuels, achieving costs as low as \$1.43 for total fuel production capacities in excess of 2500 million gge. Total capital investment (distributed pyrolyzers and centralized bio-oil processing plant) for this optimally sized distributed processing system is projected to be \$4 billion compared to \$1.6 billion for the centralized biomass processing facility. © 2008 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: distributed processing; Fischer-Tropsch liquids; FTLs; centralized catalytic synthesis; bio-oil, pyrolysis liquid

Introduction

The optimal size of advanced cellulosic biofuel plants are expected to be up to five times as large as existing grain-to-ethanol plants.¹ As much as 23 000 tons of

biomass would have to be shipped daily to such a plant, which would have serious impacts on transportation infrastructure and communities near the plant. Distributed biomass processing has the potential to alleviate biomass delivery expenses by densifying biomass prior to shipping to

a central facility for upgrading to renewable transportation fuels.

One method of densifying biomass is converting it to bio-oil via fast pyrolysis.² The specific gravity of bio-oil from switchgrass is 1.2–1.3 compared with 0.5 for pelletized switchgrass.³ Biomass pyrolysis can reduce transportation costs by converting feedstock to a liquid product. Badger and Fransham argue that fast pyrolysis reactors can be built economically at small scales, allowing their use in distributed processing systems.⁴ The high density of bio-oil is expected to result in lower transportation costs compared to chopped or baled biomass, allowing it to be transported longer distances at a reduced cost. Low transportation costs will result in larger optimally sized fuel production facilities and lower unit costs for fuel.¹

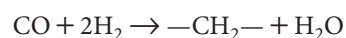
This paper considers fast pyrolysis as a means of densifying biomass for transportation with subsequent upgrading at a centralized refinery to transportation fuel. Two scenarios are considered for producing Fischer-Tropsch liquids (FTLs): centralized gasification of biomass crops and centralized gasification of bio-oil produced from distributed processing of biomass crops. Distributed processing is considered at three scales: ‘on-farm’ pyrolyzers of 5.4 ton per day (tpd) capacity; ‘small cooperative’ pyrolyzers of 55 tpd capacity, and ‘large cooperative’ pyrolyzers of 550 tpd capacity.

Background

Thermochemical conversion of biomass via gasification is likely to occur in large-scale plants processing in excess of 2000 tpd.¹ Large plants take advantage of economies of scale to reduce unit production costs. This is evident in the petroleum industries where petroleum refineries can achieve process rates equivalent to 140 000 barrels per day (about 2 billion gallons per year) due to relatively low crude

oil transportation costs. While increasing capacity generally leads to lower production costs, biomass processing facilities are constrained by feedstock availability. Because of the diffuse nature of biomass, land availability and transportation costs limit biomass conversion plants to an optimum plant size. In a previous study, the optimum plant size for a biomass FTL plant was found to be 486 million gallons of gasoline (gge) equivalent per year and 104 million gge for fast pyrolysis to bio-oil requiring biomass inputs of 1.08 and 7.69 million tons per year, respectively.¹

Biomass-to-liquids (BTL) is premised on the gasification of biomass followed by catalytic upgrading to FTLs.⁵ The primary products of Fischer-Tropsch synthesis are a mixture of light hydrocarbon gases, paraffin waxes, and alcohols according to the generalized reaction:⁶



Depending on the types and quantities of Fischer-Tropsch (F-T) products desired, either low (200–240 °C) or high temperature (300–350 °C) synthesis is used with either an iron (Fe) or cobalt catalyst (Co). Additional processing of the F-T products yields diesel fuel or gasoline.

The biomass gasification to FTLs process can be conceptualized as a five-step process. These processes, which are shown in Figure 1, include comminution, gasification, gas clean-up, water-gas shift, and catalytic processing to the desired fuels. A large number of variations and additions to this biomass gasification technology can be envisioned.⁵

Comminution consists of mechanical treatment of the feedstock to reduce its particle size and moisture content based on process requirements. Selection of reactor type and operating conditions generally dictate the extent of the pre-treatment required for optimal conversion to synthetic gas. Gasification can occur at a variety of operating conditions

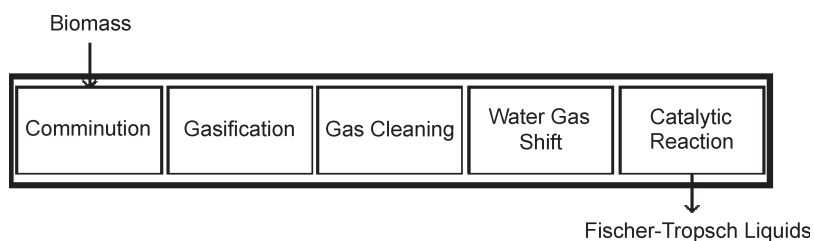


Figure 1. Flow diagram biomass to liquids production based on centralized biomass gasification.

but for F-T catalysis oxygen-blown, high-pressure (>10 bar) and high-temperature (>1000°C) gasifiers are preferred. The concept selected in this paper employs an oxygen-blown, pressurized gasifier from the Gas Technology Institute (GTI) operating at 20.3 bars and 980°C.⁷ Gas cleaning includes removal of particulate matter and trace contaminants including sulfur, chlorine, and ammonia. Some contaminants, particularly sulfur, are extremely active catalyst poisons that can limit the catalytic process and result in high expenses for catalyst replacement. Fouling of the catalyst can occur at very small concentrations measured in the parts per billion ranges.⁸ Synthetic gas composition can vary widely from different gasifier technologies and operating conditions, and catalyst requirements depend on the major metal component employed; the water-gas shift reaction adjusts the H₂:CO ratio of the syngas when required by the catalyst. Finally, an F-T reactor using a metal-based catalyst is used to convert the syngas to a mixture of hydrocarbons.

Studies of biomass gasification plants producing FTLs have found fuel costs range from \$1.10 to \$4.10 per gallon.^{9,10} We employ the frequently cited study of Tijmensen *et al.*⁷ Their analysis of a 35-million-gallon plant yielded a production cost of \$2.37 per gallon of fuel.

Distributed processing is one potential solution to supplying feedstock to large biorefineries. In this concept, small processing equipment or facilities located in close proximity to the feedstock are employed to densify the biomass prior to shipping. While different approaches to densification can be considered, this paper examines fast pyrolysis for distributed processing. The resulting bio-oil is more easily shipped to a centralized processing facility for generation of electric power^{11,12} or for upgrading to transportation fuel.¹³

Fast pyrolysis employs a rapid heating of biomass at moderate temperatures (450–500°C) in an anaerobic environment to yield liquid, solid (char), and gaseous products.¹⁴ The liquid product is known as pyrolysis liquid or more commonly as bio-oil. Bio-oil is a mixture of various organic compounds resulting from fragmentation of cellulose, hemicellulose, and lignin polymers.^{15–17} Up to 75 wt-% of the biomass weight can be converted to liquids with the balance consisting of non-condensable gas (NCG) and charcoal.¹⁸

The scheme for pyrolytic pre-treatment of biomass and bio-oil upgrading is illustrated in Figure 2. Biomass is

ground to 1–3 mm fiber lengths and dried to about 10% moisture to achieve the desired yields of bio-oil.¹⁴ The biomass is pyrolyzed and the resulting vapors passed through a particulate matter separation device before being condensed to liquid product. Numerous reactor designs have been considered,¹⁹ but fluid-bed and circulating fluid-bed reactors are most commonly employed due to ease of operation and scale-up.²⁰ Gas clean-up is used to separate solid particles, or aerosols, entrained in the gas stream. Condensation can take place over various heat exchangers to yield different bio-oil fractions.³ Bio-oil can be pumped into a tanker truck for transportation to an upgrading facility.⁴ Gasification of bio-oil followed by F-T synthesis is one method to convert bio-oil into a transportation fuel.¹³

Charcoal can provide the energy for pyrolysis although the energy value is only about \$25/ton based on coal selling for \$1.10/GJ. However, charcoal is increasingly being recognized as a valuable co-product that can be used for soil enrichment and carbon sequestration.²¹ When markets develop for sequestering carbon dioxide from the atmosphere, the value of charcoal as a carbon sequestration agent could be considerably higher than its fuel value.

Various techno-economic analyses of fast pyrolysis plants are available in the literature.^{22–25} Prior investigations estimated bio-oil production costs to range between \$0.41²² and \$1.21²⁶ per gallon. Our analysis is based on the National Renewable Energy Laboratory (NREL) report by Ringer *et al.*²⁷ for a 550 dry tpd plant producing 28 million gallons of bio-oil per year at a cost of \$0.62 per gallon. This recent (2006) analysis includes the detailed techno-economic study of pyrolysis technology that could be employed with minimum modifications in this research.

Methodology

The approach to this study consists of combining data from existing techno-economic analyses to compare the cost of producing FTLs via centralized and distributed biomass processing systems. The present analysis incorporates analytical methods for scaling plant capital and production costs, calculating feedstock delivery costs, and determining the optimal size of plants that process biomass.

Two main process configurations are considered in this paper: centralized biomass gasification (CBG) and distributed

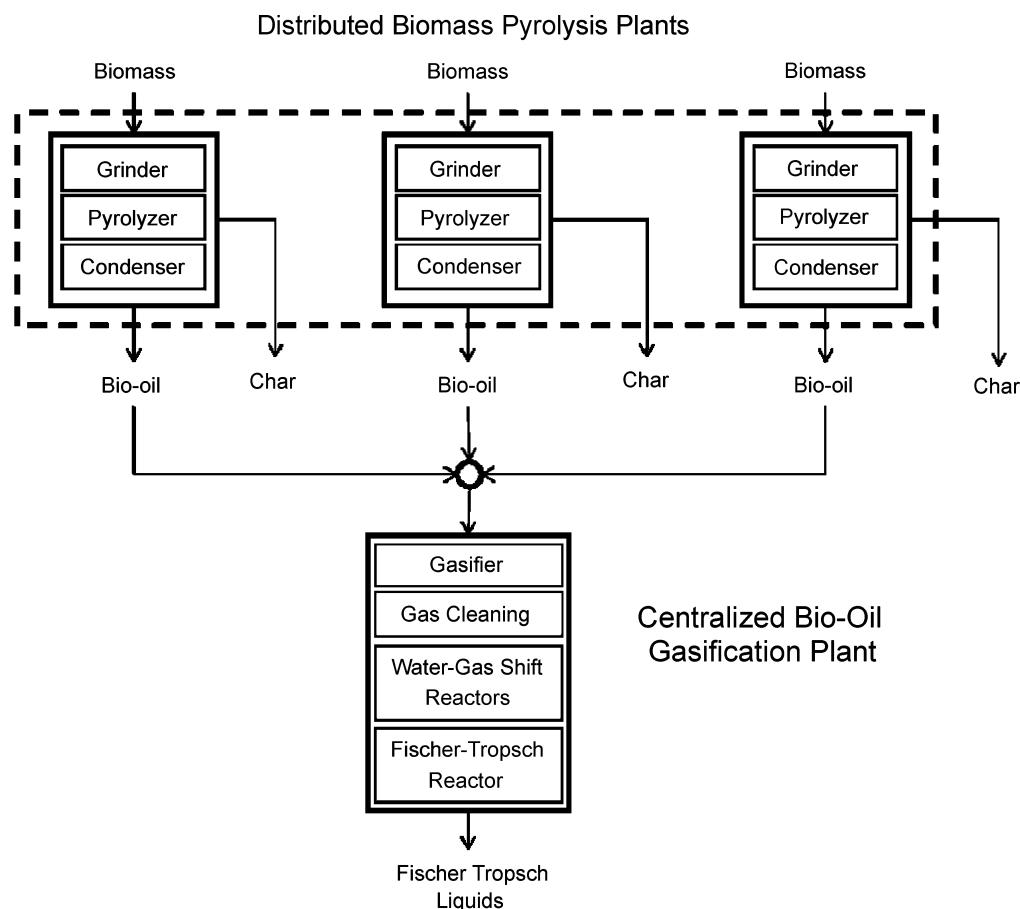


Figure 2. Distributed biomass processing diagram.

biomass processing (DBP). Distributed processing is considered at three scales: 'on-farm' pyrolyzers of 5.4 ton per day (tpd) capacity; 'small cooperative' pyrolyzers of 55 tpd capacity, and 'large cooperative' pyrolyzers of 550 tpd capacity. These distributed pyrolyzer sizes were chosen as representative of potential fast pyrolysis applications as well technology availability. For example, processing 5.4 tons of biomass per day would consume the output of an average size Iowa farm (355 acres)²⁸ yielding 5 ton/acre of biomass crop.

Plant capital costs follow a power law commonly known as economies of scale that dictates decreasing costs with increasing plant capacity. This relationship is expressed as:

$$C_p = C_{po} \left(\frac{M}{M_o} \right)^n \quad (1)$$

where C_{po} is capital cost for a plant of annual fuel production capacity M_o and n is the scale factor, which is usually

taken to be about 0.6 (the 'sixth-tenth rule'). Linear scaling ($n = 1.0$), which implies that capital costs per unit of production is invariant with the size of the plant, favors the construction of smaller plants to achieve the lowest fuel production costs.¹ Linear scaling might be achieved through mass production, which would require processing plants small enough to be factory assembled or field assembled from a few modular subsystems. Anecdotal evidence suggests a factory assembled or modular plant might be as large as a few tens of tons of biomass per day, setting the upper bound on the size of a plant that could be mass produced and achieve linear scaling. In this analysis, large plants (biomass gasification and large co-op) follow a 0.6 scale factor while the 5.4 tpd and 55 tpd distributed pyrolysis plants employ linear scaling. Table 1 shows the key capital costs of gasification to Fischer-Tropsch liquids and fast pyrolysis plants.

Operating costs typically involve various components of which some are specific to certain processes. To determine

Table 1. Biorefinery capital cost components based on reference plant size.^a

Gasification + FT (35 MMGPY FTL) ⁷	Cost (millions)	Fast Pyrolysis (28 MMGPY Bio-oil) ²⁷	Cost (millions)
Pre-treatment	\$71.6	Handling and drying	\$5.57
Gasifier	\$61.4	Pyrolysis reactor	\$3.92
Oxygen plant	\$51.1	Quench	\$1.94
Cleaning section	\$61.4	Heat recovery	\$1.14
Shift	\$3.41	Product recovery and storage	\$0.80
F-T reactor	\$20.5	Recycle	\$1.38
Gas turbine	\$23.9	Steam and power production	\$3.16
Heat recovery steam generator	\$37.5	Utilities	\$3.13
Other	\$10.2	Contingency	\$7.37
Total	\$341	Total	\$28.4

^a Only total capital costs employed in scaling calculations.

the annual feedstock cost for a given fuel output, the first step is to calculate the amount of biomass required:

$$F = M \frac{E_G}{\eta_{\text{BTF}} E_B} \quad (2)$$

where F is the total biomass input in units of tons per year, E_G and E_B represent the energy content of gasoline and biomass respectively, and η_{BTF} is the BTL fuel efficiency. The plant capacity M is given in units of gallons of gasoline equivalent (gge) per year and converted to energy units by a factor of 31.8 MJ per gallon of gasoline. The biomass energy value assumed here is 19.5 MJ/kg. The value of η_{BTF}

is process dependent and has a value of 46% for biomass to FTLs and 40% for biomass to FTLs with fast pyrolysis processing. The farm-gate cost of feedstock is assumed to be \$40 per ton for all concepts. Other plant operating cost components are process dependent and include items such as maintenance and labor charges. A full listing of all estimated process cost components and their calculation methods are included in Table 2 and Table 3.

The charcoal byproduct from fast pyrolysis has the potential of becoming an important revenue stream. Establishing a long-term carbon price is a speculative process at this time even though some markets have seen significant activity.²⁹

Table 2. Biomass gasification annual operating cost components based on reference plant size.^a

Gasification + FT (35 MMGPY)	Cost (millions)	Explanation
Capital charge	\$44.4	13% of TCI
Maintenance	\$10.2	3% of TCI
Personnel	\$2.22	Linear scaling
Dolomite	\$1.06	Linear scaling
Waste water	\$1.03	Linear scaling
ZnO consumption	\$0.03	\$33.3k/year
FT cat. insurance	\$0.44	1% Ann dep.
Key parameter	Parameter value	Explanation
Biomass to fuel efficiency	46%	MJ FTL per MJ biomass
Bio-oil to fuel efficiency ^b	58%	MJ FTL per MJ bio-oil
FTL energy value	36	MJ per liter

^a Farm-gate feedstock cost of \$40 per ton for all concepts.

^b All data comes from Ref [7] except for Bio-oil to fuel efficiency which comes from Ref [13].

Table 3. Biomass fast pyrolysis annual operating cost components based on reference plant size.^a

Fast pyrolysis (28 MMGPY)	Cost (millions)	Explanation
Water treatment	\$1.00	Linear scaling
Electricity (credit)	\$0.21	Linear scaling
Labor	\$1.34	0.6 power law scaling
Overhead	\$0.80	60% Labor
Maintenance	\$0.57	2% Equip.
Insurance/ taxes	\$0.72	1.5% TCI
Charcoal (credit)	\$1.92	\$50/ton
Key parameter	Parameter value	Explanation
Biomass to bio-oil efficiency	69%	MJ bio-oil per MJ biomass
Char yield	16.2%	Kg char per Kg biomass
Bio-oil energy value	19.7	MJ per liter

^a All data adapted from Ref [28] except for Charcoal (credit) which comes from Ref [30].

A \$50/ton credit is assigned to charcoal production, which assumes the charcoal (85% carbon) has value as a carbon sequestration agent equivalent to \$16/ton carbon dioxide. The charcoal, which contains various inorganic compounds, also has potential as fertilizer³⁰ and soil organic matter,²¹ but this has not been factored into the charcoal credit.

For the centralized biomass processing case, the average delivery distance to the central plant from a circular area surrounding the central plant is given by:

$$\bar{r}_{circle} = \frac{2}{3} \tau \sqrt{\frac{F}{\pi Y f}} \quad (3)$$

where τ is the tortuosity factor, which is a function of a region's road development and reflects the ratio of actual distance traveled to the straight line distance to a location.³¹ A tortuosity factor of 1 corresponds therefore to a straight line trajectory between two given points. A value of 1.5 is assumed here, which is characteristic of a rectangular grid road layout. Y is the biomass yield in tons per acre. The factor f is the fraction of land surrounding the plant that is devoted to biomass crops. The exact value is site-specific and depends upon land availability, environmental concerns, and other local considerations; here a value of 60% is assumed. Once the average delivery distance is calculated, it is multiplied by a unit cost for biomass transportation (\$0.71³² per ton per mile).

For the distributed biomass processing case, a square grid is assumed around the centralized bio-oil processing plant

with distributed pyrolysis plants located at the center of the squares making up the grid. The average biomass transportation distance to a pyrolysis plant is equal to the average distance from a random point in the square to the center of the square:³³

$$\bar{r}_{square} = \frac{1}{6} \tau \sqrt{\frac{F}{Y f}} (\sqrt{2} + \ln(1 + \sqrt{2})) \quad (4)$$

Also needed is the average distance that bio-oil must be shipped from distributed pyrolysis plants to the centralized bio-oil processing plant. This quantity depends upon the amount of biomass that must be converted to bio-oil and the size of the distributed pyrolysis plants, as shown in Fig. 3. From this figure a power law for calculating bio-oil transportation distance was determined:

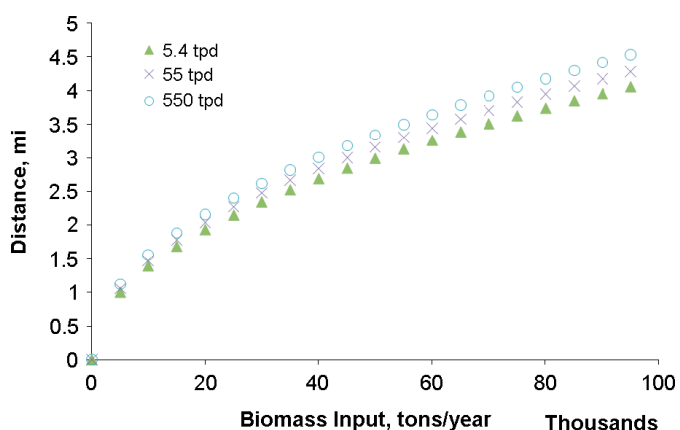


Figure 3. Average bio-oil delivery distance to central plant.

$$\bar{r}_{grid} = 0.423 \tau \left(\frac{F}{F_{plant}} \right)^{0.476} \sqrt{\frac{F_{plant}}{Yf}} \quad (5)$$

A larger mass of bio-oil can be transported than of biomass by a single truck by virtue of its higher volumetric density. This is reflected in a lower bio-oil unit transportation cost. The unit cost for bio-oil transportation is assumed to be \$0.14 per ton per mile.³⁴

Using the above information on processing costs and transportation costs, the unit cost of biofuel as a function of total fuel output was calculated for centralized biomass processing and distributed biomass processing with subsequent centralized upgrading to FTLs. As described in a previous paper, an optimal size for minimum fuel production costs is expected.¹

Results

Figure 4 plots fuel cost as a function of fuel production capacity for centralized biomass gasification (CBG) and three scales of distributed biomass processing (DBP). CBG has a clearly discernable minimum cost of \$1.56 for fuel production that occurs at a fuel production capacity of 550 million gge. From Figure 4, fuel cost for DBP appears to decrease monotonically with increasing fuel production capacity. In fact, DBP also has optimal plant sizes, but these occur at fuel production capacities well in excess of 2.5 billion gge. Fuel cost also decreases for DBP as the size of the distributed pyrolyzers gets smaller. For sufficiently large fuel production capacity, DBP is more cost-effective than CBG.

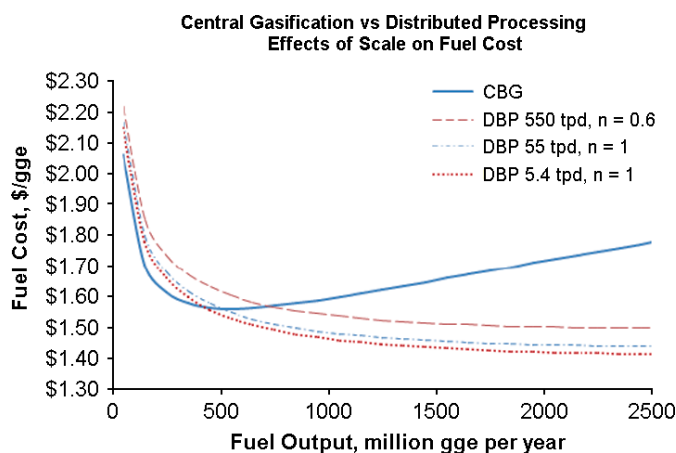


Figure 4. Fuel production cost at different plant sizes for central and distributed processing.

This occurs at 450 million gge for 5.4 tpd pyrolyzers and 700 million gge for 550 tpd pyrolysis plants.

Figure 5 shows the major cost components for the four biomass processing scenarios for total fuel production capacity of 550 million gge which is the optimum capacity for the centralized biomass processing concept. Differences in fuel costs are essentially indistinguishable for these four scenarios at this capacity ($\pm 30\%$ uncertainty); however, there are major differences in the distribution of major cost components for CBG and DBP. Operation and maintenance costs are lower for CBG because of favorable economies of scale. Biomass costs are also lower for CBG because a centralized plant has higher thermodynamic efficiencies. On the other hand, transportation costs for DBP are less than half that of CBG because of the short distances that biomass has to be hauled for a distributed system (0.56 miles compared to 37 miles). Keep in mind that as total fuel capacity increases beyond 550 million gge, biomass transportation costs for CBG balloons while it increases only modestly for DBP because transportation costs per mile for bio-oil is only 20% the cost of biomass transportation. This difference in transportation costs also explains why distributed processing employing the smallest pyrolyzers (5.4 tpd) yielded the lowest production costs shown in Fig. 5.

Table 4 summarizes capital costs for the four biofuel production systems. Capital costs for the 550 million gge CBG plant totals \$1.63 billion. Capital costs for the centralized bio-oil plant in the DBP system is only \$1.6 billion because of the simpler feedstock handling system for bio-oil compared

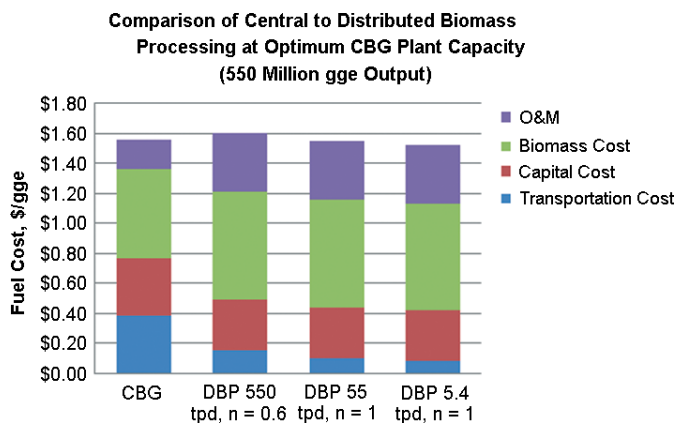


Figure 5. Operating cost components at optimum centralized processing output size.

Table 4. Capital costs for centralized and distributed plant scenarios at 550 million gge capacity.

	CBG	DBP	
	Central	Central	Distributed
Number of plants	1	1	55
Capital cost (billions)	\$1.6	\$1.4	\$2.6
Total	\$1.6	\$4.1	
Capital costs for DBP based on 550, 55, and 5.4 tpd pyrolyzers are identical within ±5% uncertainty.			

to biomass. Of course, the distributed pyrolyzers required for DBP add substantially to the capitals cost of this approach to biofuels. Large cooperative pyrolyzers (550 tpd) cost \$47.8 million each which comes to a \$2.63 billion investment for the pyrolyzers alone. Total capital cost of DBP employing large cooperative pyrolyzers would come to \$4.1 billion. The small cooperative pyrolyzer and on-farm pyrolyzer systems have identical aggregate costs within a 5% uncertainty.

A sensitivity analysis was conducted to study the effects of key variables: biomass yield, fuel conversion efficiency, transportation cost. Charcoal credit sensitivity was included in the pyrolysis technologies analysis. While there are numerous factors that could greatly affect the cost of BTL fuels, the impact of these selected variables can easily be studied in this model for both CBG and DBP. Figure 6 includes the results of this analysis.

As shown in Figure 6, there are various factors that can significantly affect the cost of biofuel production. Fuel conversion efficiency, a reflection of process performance, indicates that improving conversion efficiency from 46 to 55% can reduce fuel costs by \$0.25 per gallon produced for centralized biomass processing. Due to the large biomass delivery distances that CBP would require, it is no surprise that a 20% increase in transportation costs can increase fuel production costs by \$0.08 per gge (from \$1.56 to \$1.64 per gge). In this analysis, low crop yields would require an increase in the area of cropland employed to grow biomass which would raise the biomass delivery distance and subsequently production costs. A 20% decrease in crop yields would raise fuel production costs by \$0.04 per gge. DBP has a markedly lower sensitivity to transportation costs and biomass yields due to the reduction in average biomass delivery distances. In fact, a 20% increase in biomass delivery costs would only increase DBP fuel costs a bit more than a tenth of a cent per gge. DBP is affected by process efficiency with potential \$0.23 per gge reduction in cost for 20% increase in process efficiency. Charcoal cost also stands to have a significant impact on fuel costs; a 50% variation in the cost of charcoal assumed here would alter fuel costs by \$0.09 per gallon. These results underscore the importance of process efficiency as well as mark the vulnerability of a centralized biomass processing scenario to variations in the biomass harvesting and transportation system.

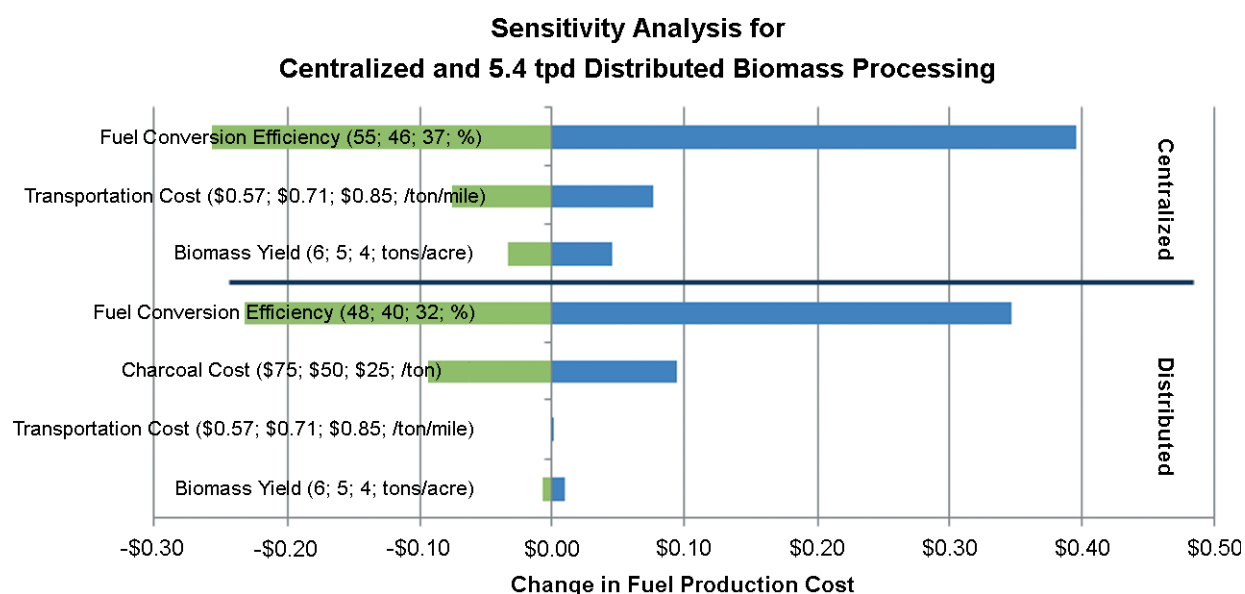


Figure 6. Sensitivity analysis of 550 million gge for centralized and 5.4 tpd distributed processing.

Conclusions

Distributed processing of biomass to bio-oil followed by gasification of the bio-oil and catalytic conversion of syngas to FTLs offers production cost advantages over a more traditional system of centralized biomass gasification and F-T synthesis at fuel production capacities exceeding 550 million gge per year. Higher operation and biomass costs of the distributed processing system are offset by much lower transportation costs of bio-oil compared to biomass. An additional advantage of distributed processing is a low sensitivity to variations in delivery costs and crop yields. This is important because delivery costs are hard to predict due to variations in transportation fuel costs, and regional considerations.

On the other hand, the distributed processing system comes at much higher capital cost than the centralized biomass processing system. Capital costs will be a major factor in future technology selection. Distributed processing incurs a large capital expense that will require solid financing and long-term commitments.

As shown in this analysis, large-scale production of transportation fuel from biomass will require large investments in the order of billions of dollars. Distributed processing of biomass could be necessary at large production scales to lower fuel transportation costs, and reduction in capital investment expenses would allow for a faster implementation of these advanced biomass conversion pathways.

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References

1. Wright M and Brown R C, Establishing the optimal sizes of different kinds of biorefineries, *Biofuels Bioprod Bioref* **1**:191–207 (2007).
2. Mohan D, Pittman CU Jr and Steele PH, Pyrolysis of wood/biomass for bio-oil: a critical review, *Energy & Fuels* **20**:848–889 (2006).
3. Boateng AA, Daugaard DE, Goldberg NM and Hicks KB, Bench-scale fluidized-bed pyrolysis of switchgrass for bio-oil production, *Ind Eng Chem Res* **46** (7):1891–1897 (2007).
4. Badger PC and Fransham P, Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs – a preliminary assessment, *Biomass Bioenergy* **30**:321–325 (2006).
5. Demirbas A, Converting biomass derived synthetic gas to fuels via Fischer-Tropsch synthesis, *Energy Source* **29**(16):1507–1512 (2007).
6. Dry ME, Sasol Fischer-Tropsch processes. *Appl Ind Catal* **2**:167–213 (1983).
7. Tijmensen JAM, Faaij APC and Hamelinck CN, Exploration of the possibilities for production of Fischer-Tropsch liquids and power via biomass gasification, *Biomass Bioenergy* **23**:129–152 (2002).
8. Turk BS, Merkel T, Lopez-Ortiz A, Gupta RP, Portzer JW, Kishnam G, Freeman BD and Fleming G K, Novel technologies for gaseous contaminants control, DOE Report DE-AC26-99FT40675 (September 2001).
9. MITRE Corporation, Techno-economic assessment of biomass gasification technologies for fuels and power (1996).
10. Netherlands Agency for Energy and the Environment, Technical and Economic Data Biomass-Bases Energy Conversion Systems for the Production of Gaseous and/or Liquid Energy Carriers. Report No. GAVE-9915, Novem. (2000).
11. Barker SN, Gasification and pyrolysis – routes to competitive electricity production from biomass in the U K, *Energy Convers Manage* **37**(6–8): 861–866 (1996).
12. Mitchell C P, Bridgwater AV, Stevens DJ, Toft AJ and Watters MP, Technoeconomic assessment of biomass to energy, *Biomass Bioenergy* **9**:205–226 (1995).
13. Henrich E, Raffelt K, Stahl R and Weirich F, Clean syngas from bio-oil/char slurries. *Proceedings of the Science in Thermal and Chemical Biomass Conversion Conference, Vancouver Island, Canada, August 30 – September 2, 2004* (2005).
14. Bridgwater AV, Toft AJ and Brammer JG, A Techno-economic comparison of Power production by biomass fast pyrolysis with gasification and combustion, *Renew Sust Energy Rev* **6**:181–248 (2002).
15. Elliott DC, Analysis and comparison of biomass pyrolysis/gasification condensates - final report. PNL-5943, Contract DEAC06-76RLO 1830 (1986).
16. Peacocke GVC, Russel PA, Jenkins JD and Bridgwater AV. Physical properties of flash pyrolysis liquids, *Biomass Bioenergy* **7**:169–178 (1994).
17. Fagerman's L, Chemical and physical characterisation of biomass-based pyrolysis oils. literature review. Espoo 1995, Technical Research Centre of Finland.
18. Bridgwater AV, Czernik S and Piskorz J, An overview of fast pyrolysis in *Progress in Thermochemical Biomass Conversion* ed by Bridgwater AV. Blackwell Science, Oxford, pp 977–997 (2001).
19. Brown RC and Holmgren J, Fast pyrolysis and bio-oil upgrading <http://www.ars.usda.gov/sp2UserFiles/Program/307/biomasstoDiesel/RobertBrown&JenniferHolmgrenpresentationslides.pdf> [September 2007].
20. Bridgwater AV and Peacocke GVC, Fast pyrolysis processes for biomass, *Renew Sust Energy Rev* **4**:1–73 (2000).
21. Lehmann J, Bio-energy in the black, *Front Ecol Environ* **5**:381–387 (2007).
22. Cottam ML and Bridgwater AV, Techno-economic modeling of biomass flash pyrolysis and upgrading systems, *Biomass Bioenergy* **7**:267–273 (1994).
23. Gregoire CE and Bain RL, Technoeconomic analysis of the production of biocrude from wood, *Biomass Bioenergy* **7**:275–283 (1994).
24. Gregoire Catherine E, Technoeconomic Analysis of the Production of Biocrude from Wood. NREL/TP-430-5435. National Renewable Energy Laboratory, Golden, CO (1992).

25. Solantausta Y, Beckman D, Bridgwater AV, Diebold JP and Elliot DC, Assessment of liquefaction and pyrolysis systems, *Biomass Bioenerg* **2**:279–297 (1992).
26. Mullaney H, Technical, environmental and economic feasibility of bio-oil in New Hampshire's North Country. University of New Hampshire, Durham, NH (2002).
27. Ringer M, Putsche V and Scahill J, Large-scale pyrolysis oil production: a technology assessment and economic analysis, NREL Report NREL/TP-510-37779 November (2006).
28. USDA, Number of Iowa farms and average farm size 1950–2006, USDA, National Agricultural Statistics Service, Iowa Agricultural Statistics Bulletin http://www.nass.usda.gov/Statistics_by_State/Iowa/Publications/Annual_Statistical_Bulletin/2007/07_6.pdf [September 2007].
29. Carbon prices - Climate Change Projects Office Guide in association with Department for Environment Food and Rural Affairs. Published April 2005. <http://www.berr.gov.uk/files/file21144.pdf>
30. Anex RP, Lynd LR, Laser MS, Heggenstaller AH and Liebman M, Growing energy, closing cycles: the potential for enhanced nutrient cycling through the coupling of agricultural and bioenergy systems, *Crop Sci J* **47**:1327–1335 (2007).
31. Jenkins BM, A comment on the optimal sizing of a biomass utilization facility under constant and variable cost scaling, *Biomass Bioenerg* **13**:1–9 (1997).
32. Birrell S, Personal communication, Iowa State University (2007).
33. Rogerson PA, *Statistical methods for geography: a student guide* Sage Publications, Thousand Oaks, CA (2006).
34. Borjesson P and Gustavsson L, Regional production and utilization of biomass in Sweden, *Energy* **21**:747–764 (1996).